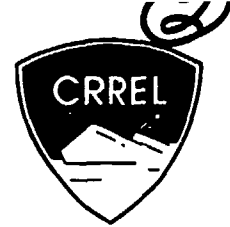AD-A276 508

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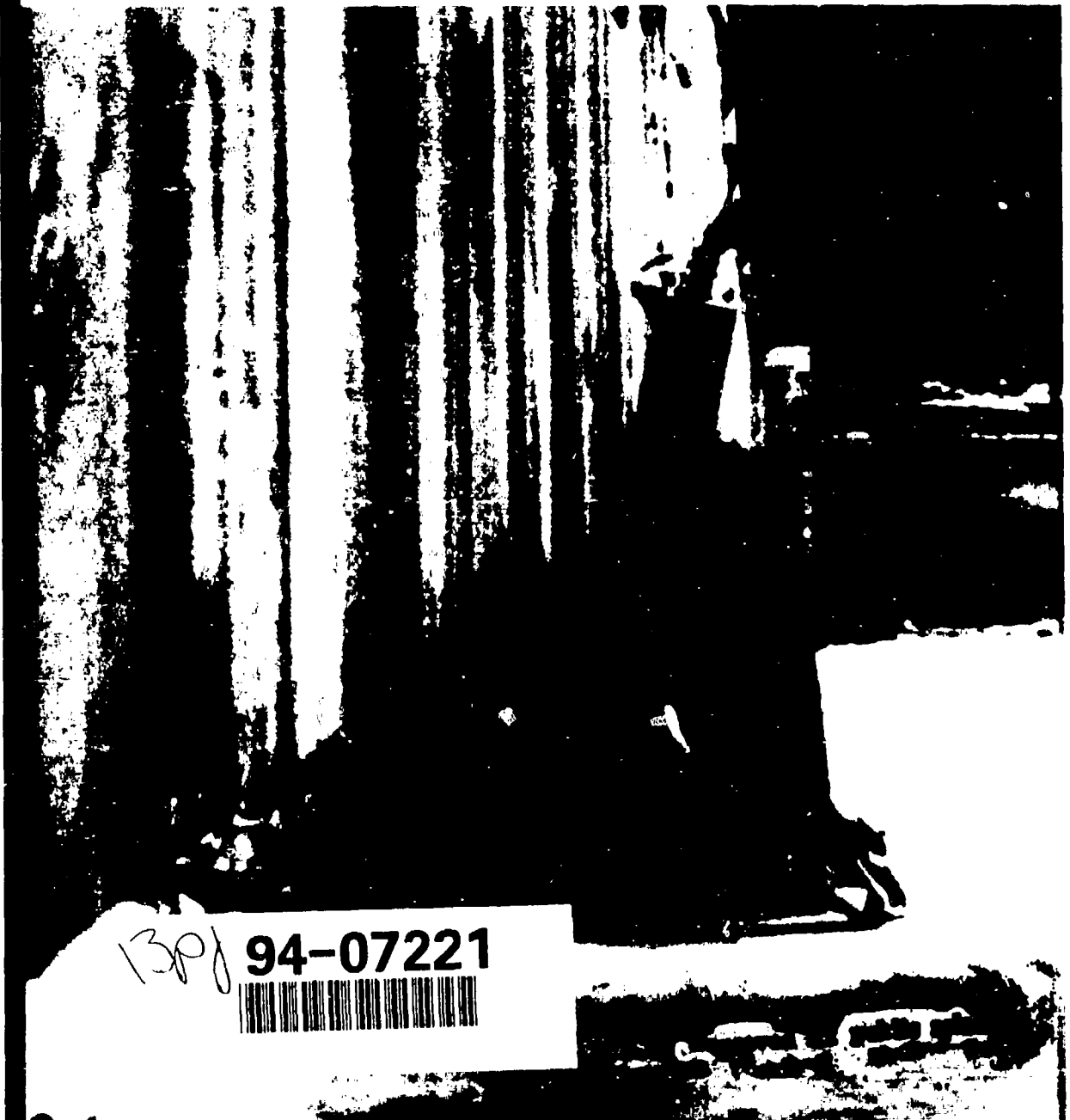
CRREL

Automatic, Continuous River Stage Measurement with a Millimeter-Wave FM-CW Radar

Norbert E. Yankielun and Michael G. Ferrick

December 1993

94-07221

Abstract

River stage measurements at many locations are fundamental for the analysis of dynamic events on rivers, including ice breakup. But, these data are frequently unavailable. A high-resolution, broadband millimeter-wave (26.5 to 40 GHz) Frequency Modulated-Continuous Wave (FM-CW) radar, with real-time data acquisition and digital signal processing capability, was mounted from fixed locations on bridges over the Connecticut River to continuously acquire, process, store and display river stage data during controlled releases of water from a hydropower dam. The radar system provided continuous stage data of accuracy comparable to those acquired by a survey team and a permanent U.S. Geological Survey stream gauging station. The system can be rapidly installed and is capable of acquiring data, including event timing, at 1-, 10- or 60-second intervals, around-the-clock, without operator interaction or visual readings. The system sensor can be remotely mounted and monitored, thereby minimizing safety hazards to personnel using direct measurement techniques.

Cover: *Radar deployed from the covered bridge between Cornish, New Hampshire, and Windsor, Vermont.*

CRREL Report 93-24

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PREFACE

Automatic, Continuous River Stage Measurement with a Millimeter-Wave FM-CW Radar

NORBERT E. YANKIELUN AND MICHAEL G. FERRICK

INTRODUCTION

Radar systems are commonly used in hydrological and other geophysical applications, particularly for measuring ice thickness on freshwater rivers and lakes. The majority of the effort, to date, has been with radars operating at frequencies from less than 1 to 12 GHz that are able to resolve ice thicknesses in the range of 10 to 20 cm (Page and Ramseier 1975, Venier and Cross 1975, Chudobiak et al. 1978, Batson et al. 1984, Arcone 1991). Additionally, radars have been used for other geophysical remote sensing applications (Wittmann and Stoltenberg 1981) and for snow stratification investigations (Ellerbruch and Boyne 1984, Gubler and Hiller 1984). Radars are also commonly used as altimeters, capable of measuring the range from an aircraft to the ground (Skolnik 1980).

Recently, an airborne millimeter-wave (MMW) FM-CW (frequency modulated-continuous wave) radar system has been developed that can do high-resolution, continuous profiling of river and lake ice (Yankielun 1992, Yankielun et al. 1992, 1993). It can resolve distance in air to as little as 1.1 cm, and can resolve freshwater ice sheet thicknesses to a minimum of 3 cm ±10%.

Accurate river stage measurement is critical to flood hazard and water resource assessment. In particular, the importance of river surging on the processes of dynamic ice breakup and ice-induced flooding is widely recognized. However, stage measurement on rivers that experience dynamic breakup can be difficult. Ice rubble piles on the banks, darkness and ice scour of the bed frequently stop measurements by survey teams and instruments requiring that cables be placed in the river. It is clear that measurement systems that are readily installed and not affected by light and ice motion conditions are needed. River stage measurement with high-resolution MMW FM-CW radar provides a remotely mounted and monitored, continuously recording alternative to the established techniques. Radar measurements from above the river keep personnel safe from the physical hazards of direct observation and eliminate data reliability problems caused by scour. As an economy, the radar system used for stage measurement is also useful for measuring ice thickness (Yankielun et al. 1993).

FM-CW RADAR

In an FM-CW system (Fig. 1), the output of an MMW linear Voltage Controlled Oscillator (VCO) is transmitted toward the target. The energy reflected from the target, delayed by the round-trip propagation time $2t_p$, is mixed with a sample of the VCO output. The difference frequency F_r is proportional to the distance to the target and can be determined using spectral analysis techniques.

Distance d in meters is calculated in terms of frequency according to the relation

$$d = \frac{(F_r)(t_{swp})c}{2(BW)(n_{air})} \tag{1}$$

where F_r = difference frequency due to radar reflection (Hz)
t_{swp} = FM-CW sweep time (s)
c = velocity of light in vacuum (m/s)
BW = FM-CW swept bandwidth (Hz)
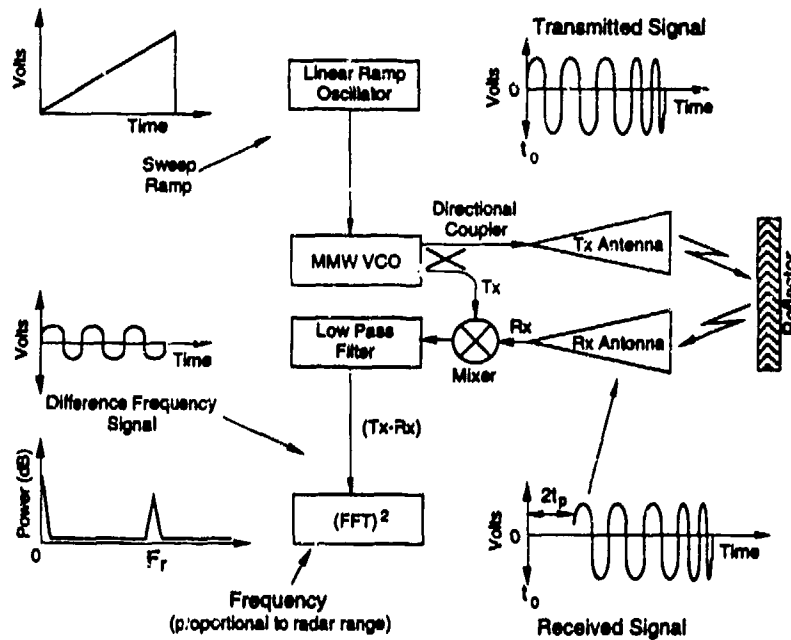n_{air} = index of refraction of air = 1.

Figure 1. FM-CW radar system.

Figure 2 shows a processed FM-CW radar return from a water surface, where

$$d = \frac{(11.4 \text{ kHz})(0.066 \text{ s})(3\times10^8 \text{ m/s})}{2(13.5 \text{ GHz})(1)} = 8.36 \text{ m}.$$

The broader the swept bandwidth is, the greater is the distance resolution. For the system discussed here, the bandwidth, as available from the sweep oscillator, is 26.5 to 40 GHz. There is a tradeoff between range and resolution as there is a limit on the number of time series samples that can be taken during a given sweep at a set sample rate. The greater the maximum radar range, the fewer samples that can be allocated to a small frequency segment of interest. In this application, the 2048 digitized time series samples of each scan are transformed to a power spectrum consisting of 1024 discrete frequencies from 0 to the one-half the sample rate; the range resolution is approximately 1.1 cm.

When a sheet of cold, dry freshwater ice is encountered by the radar, two pulses are reflected, one each from the air/ice and ice/water interfaces. The ice thickness t_i in meters is found from the separation of the two difference frequencies according to the relation

$$t_i = \frac{(F_{r2} - F_{r1})(t_{swp})c}{2(BW)(n_{ice})} \tag{2}$$

where F_{r1} = difference frequency due to air/ice interface reflection

F_{r2} = difference frequency due to ice/water interface reflection

n_{ice} = index of refraction of freshwater ice = 1.78 (Cumming 1952).

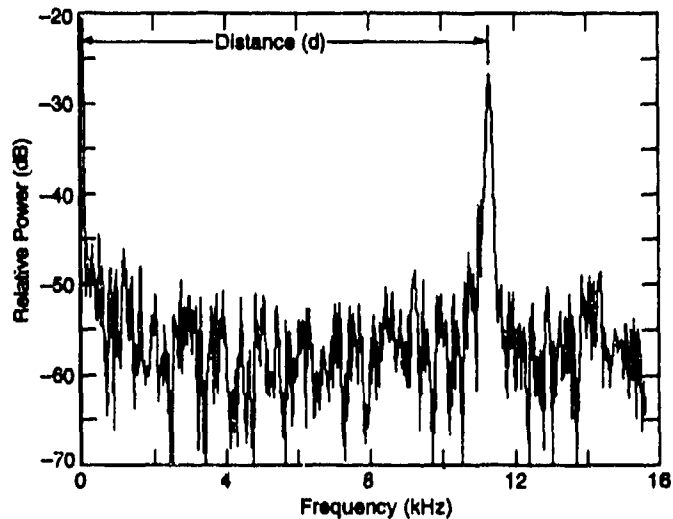The significant contrast between indices of refraction of air and water causes radar scans obtained

Figure 2. Typical frequency-transformed FM-CW radar signal reflected from an air/water interface with radar range indicated.

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from warm and wet ice, saturated snow cover, surface melt pools or open water to exhibit a single reflection pulse, since virtually all of the transmitted energy is reflected at this interface. The minute component of transmitted energy coupled through this interface is predominantly absorbed by the wet medium.

SYSTEM DESCRIPTION

The system used for this experiment (Fig. 3) is a modified version of a successfully deployed MMW FM-CW radar system (Yankielun 1992, Yankielun et al. 1992). Here, the system consists of an HP 3314A function generator programmed to produce a 0- to 10-V linear ramp with a period of 0.066 seconds that is used to drive the MMW VCO. A second output on the signal generator provides a pulse, synchronized with the start and end points of the linear ramp, to trigger an HP 3660A Dynamic Signal Analyzer and the 12-bit analog-to-digital converter (A/D) internal to the laptop computer. Data acquisition software controlling the A/D converter is programmed to count the synchronization pulses from the HP 3314A and digitize every n^{th} radar scan into 2048 time series samples. Here, n is chosen to permit acquisition of one scan every 1, 10 or 60 seconds, as
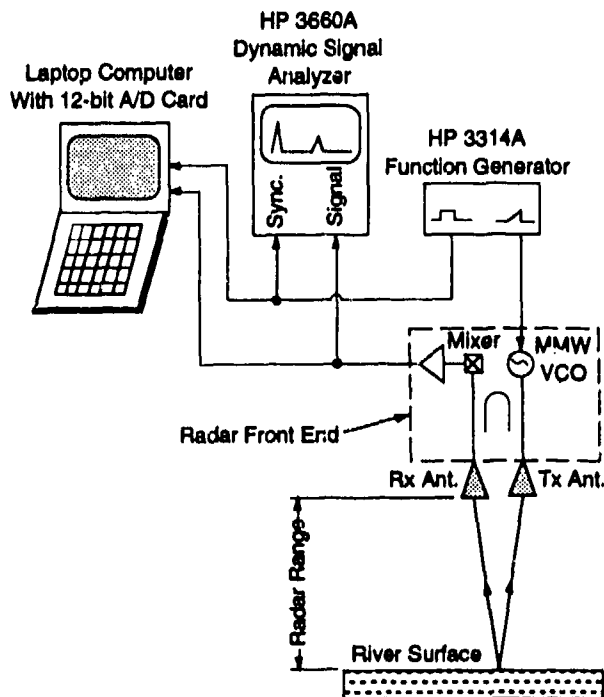
appropriate to fully characterize an event. Data are sampled at 31.25 kHz, providing a maximum radar range of 11.46 m in air. Each digitized scan is sequentially stored in binary format on the laptop computer hard disk for later Digital Signal Processing (DSP) and analysis. A time stamp and index number are stored for each acquired scan in ASCII format in a second data file. The time stamp data are used in conjunction with the radar scan data to precisely time events. In parallel with this data acquisition operation, the HP3660A Dynamic Signal Analyzer is used to monitor the process and display real-time ranging information.

The radar front-end—consisting of the VCO, waveguide components, transmit and receive an-

Figure 4. MMW FM-CW radar front-end suspended by a cable from a window in the covered bridge over the Connecticut River at Windsor, Vermont. Initial range from the radar to the river surface was approximately 10 m. The slightly off-nadir antenna look angle, while not optimum, did not appreciably affect radar data acquisition.

Figure 3. Components of the MMW FM-CW radar system used here.

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Figure 5. Radar system control and data acquisition components in operation on the covered bridge over the Connecticut River at Windsor, Vermont. Visible are the laptop computer (upper left), dynamic signal analyzer and sweep generator (lower left) and a battery box power supply for the radar front-end (lower right).
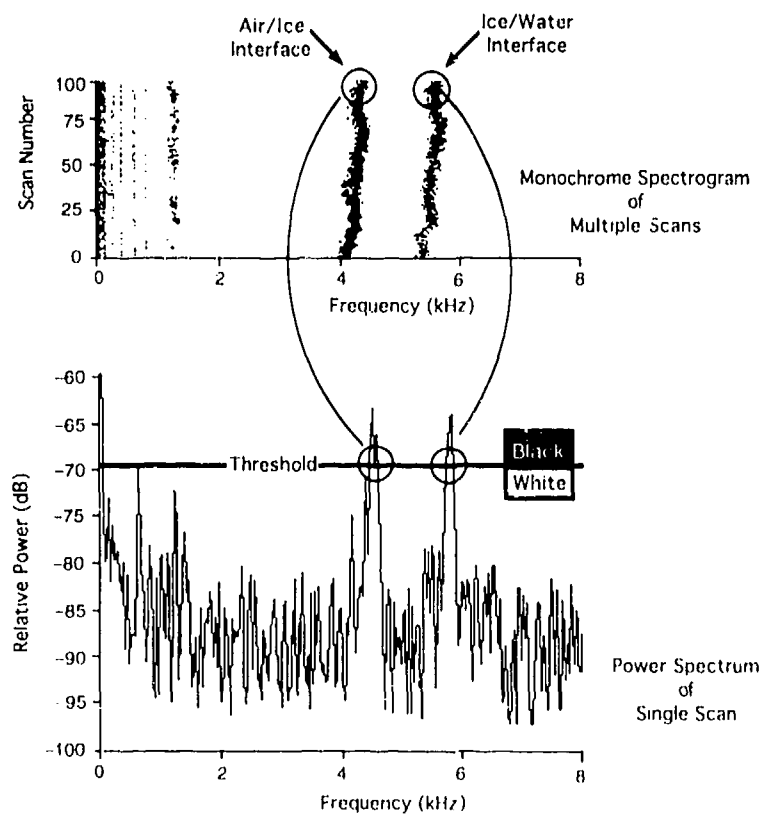

Figure 6. Relationship of a monochromatic multi-scan spectrographic display to a single-scan power spectrum of radar data.

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tennas, mixer and audio amplifier—is mounted with the antennas pointing at a normal incidence from a fixed point overlooking the river (Fig. 4). The remaining control and acquisition components are remotely located and connected to the front-end via power and signal cables (Fig. 5). The system is powered by a portable, gasoline-driven electric generator.

After a survey is completed, the raw time series radar data are processed and displayed using a Macintosh II computer equipped with a Spectral Innovations, Inc., DSP coprocessor. Each radar scan was digitized to provide 2048 time series samples, transformed into a power spectrum, processed with a Hanning window algorithm to suppress the effect of spectral sidelobes that might otherwise mask lower level signals, and displayed in a continuous spectrographic form. In a spectrogram, discrete signal magnitudes are represented by a range of color or gray scale. With monochromatic graphics, this results in signal magnitudes above a preset threshold appearing as black and below that threshold as white (Fig. 6). The DSP software permits a threshold level to be set for a clear differentiation of the radar pulse reflection from the river surface. Here, as a result of the selected threshold level intersecting reflection pulses at a point somewhat below the pulse peak, the trace appears fairly broad. A multi-color spectrographic display provides significantly greater graphical resolution than is possible with monochromatic display by indicating intermediate levels of signal intensity with a 256-shade color gradient.

RESULTS AND DISCUSSION

Experiments over open water and an ice cover were conducted to ascertain the viability of this technique of remotely obtaining river stage data.

Open water experiment

The radar system was deployed over open water from a bridge across the Connecticut River, near West Lebanon, New Hampshire, to acquire river stage data prior to and during the transition from minimum flow to full turbine operation at the Wilder Dam hydropower station, 2 km upriver. Unfortunately, the height of this bridge above the river made it impossible to suspend the radar sensor within its specified operational range with the cables available. However, a faint trace that accurately tracked the river stage was visible in the spectrogram of the processed data. This trace is a vestigial artifact attributable to "aliasing" in the digital
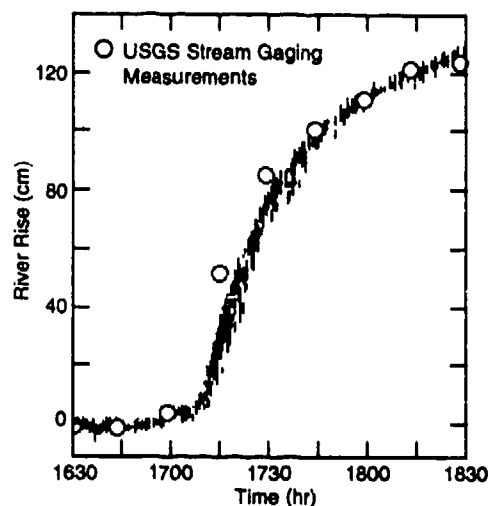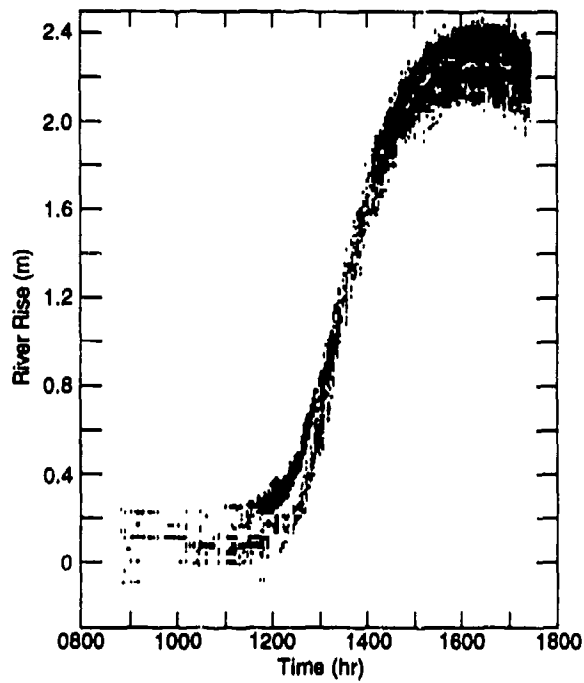

Figure 7. Spectrogram of radar ranging data indicating time and river rise during the experiment over open water. U.S. Geological Survey stream gauging measurements at the same location are also indicated.

sampling process (Oppenheim and Schafer 1975, Stanley et al. 1984). Aliasing is a well known and unwanted manifestation that can occur when digitally sampling data. Typically, it is prevented or attenuated to negligible levels by appropriate analog filtering prior to digital sampling. Here, however, aliasing was exploited, in effect, to extend the range of the radar and provide an accurate representation of river stage (Fig. 7). While the spectrogram trace is not as distinct as that obtainable with the sensor placed within the specified operational range, it closely tracks the data from the gauging station. Trace clarity can be significantly improved when the system is operated within its specified range limits.

Ice cover experiment

The radar system was deployed from a bridge over the Connecticut River on 6 March 1992, at Windsor, Vermont, to capture the shape of a large water surge released from the Wilder Dam upriver during a study of controlled ice breakup (Ferrick and Mulherin 1989). Here, the radar sensor was placed within its operational range, permitting acquisition of stage data with improved trace clarity. A spectrogram of the raw stage data is shown in Figure 8a. Simultaneously with the radar, a survey crew acquired stage data at the same location with a level and stadia rod.

The power spectrum data for each radar scan were further processed to precisely derive the radar range from the location of the pulse with the maxi-

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a. Raw data.
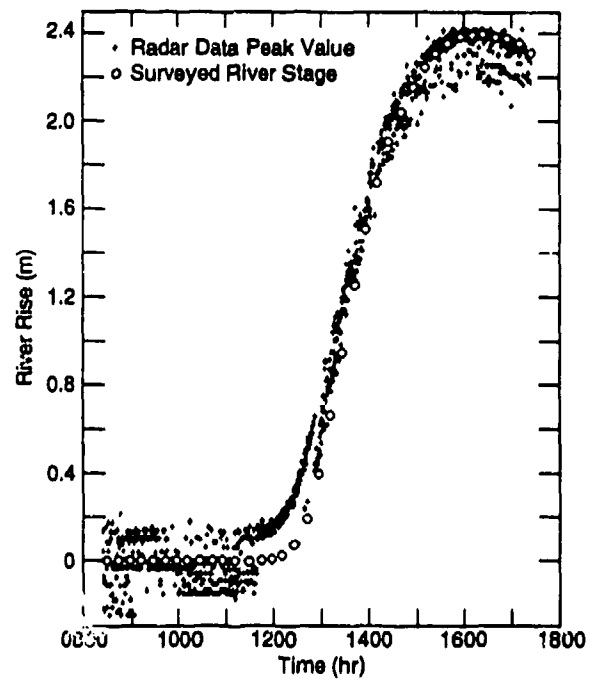
b. Data processed with maximum peak locating algorithm.

c. Smoothed data.

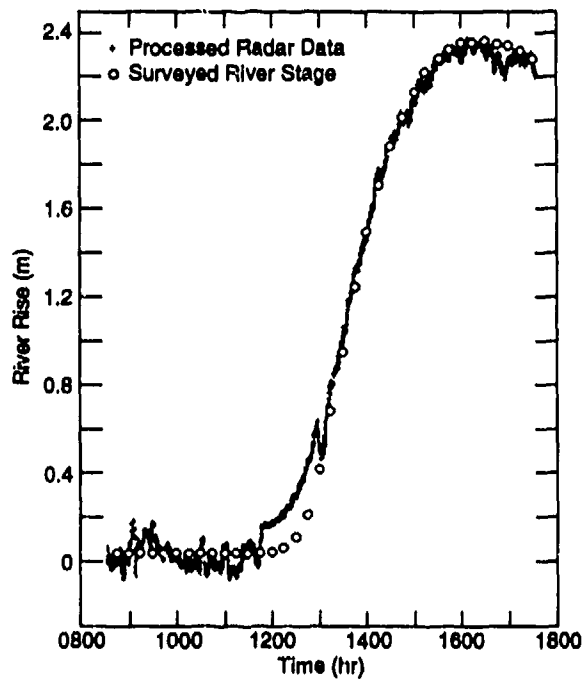Figure 8. Spectrograms of radar ranging data indicating time and river rise during the experiment over an ice cover.

mum magnitude in each scan. The location of the pulse with the greatest magnitude in each radar scan represents the range to the target that provides the greatest reflectivity. Here, there are three possible targets to which the maximum magnitude pulse in a scan may be attributable: an air/ice inter-face, an ice/water interface or an air/water inter-face. It has been shown (Yankielun 1992) that in the case of cold, dry, freshwater ice, there may be as much as a ±15 dB difference between the magnitude of the air/ice and ice/water reflected pulses within a given scan, mainly attributable to variations in the

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surface and volume scattering of the radar signal. Therefore, in any given scan taken over cold, dry ice, the air/ice or ice/water pulse may be identified by the peak finder algorithm as the pulse with the maximum magnitude. This results in a possible scan-to-scan variation of range proportional to the thickness of the ice sheet. Figure 8b shows the result of processing with the maximum peak locating algorithm. Data from the survey measurements are overlaid for comparison.

To smooth the data, a running 10-point averaging algorithm was applied to the maximum peak magnitude data, with the results shown in Figure 8c. Here, the overlaid survey data accurately track the radar data after 1300 hours. Prior to this, the averaged radar data are either systematically higher or shift irregularly about the survey data. The difference between the radar and the survey measurements is caused by shifting ice plates in the near bank area as they interact with each other and the river bed. Locating the radar system further from the bank over smooth and free floating sheet ice would provide accurate river stage measurement.

At 0730 hours on 30 March 1993, the radar was again deployed over the Connecticut River, at Windsor, Vermont, to obtain stage data during a natural breakup. The ice had broken into rubble and was already moving when the radar system was set up and activated. The stage data were acquired every 20 seconds; Figure 9 shows the resulting stage radar spectrograph. The wide variation seen in the left half of the spectrograph trace results from the variation

Figure 10. Comparison of radar and surveyed river stage data obtained on the Connecticut River near Ascutney, Vermont, on 30 March 1992.
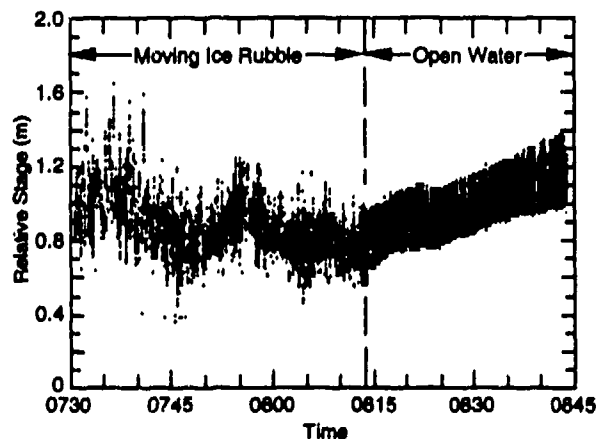

Figure 9. Stage data obtained during 30 March 1992 showing the transition from a moving rubble ice cover to open water on the Connecticut River near Windsor, Vermont.
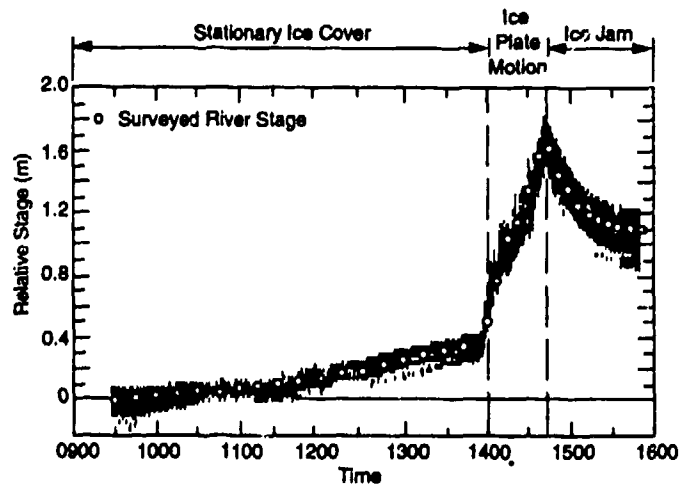
in rubble height above the water surface, and indicates the trend in river stage. During the second half of the event, the ice rubble had passed from under the radar and the resulting scan-to-scan consistency is indicative of a response from open water. No surveyed stage data were available for comparison to the radar measurements during this portion of the breakup event owing to the hazard presented by the moving ice. The stage increase following the passage of the ice continued over the next hour, but at a diminishing rate. During this same period, the stage was steady at a stream gauge 23 km upstream in open water, and at a survey station 8 km downstream where the river had a stationary ice sheet. Together, these data indicate that the rising stage at Windsor was local, resulting from the ice stopping and a backwater developing behind the newly formed jam.

At 0930 hours on 30 March 1993, the radar system was redeployed from another bridge over the Connecticut River at Ascutney, Vermont, approximately 8 km downstream of the Windsor site. Figure 10 compares the radar spectrogram with surveyed stage data at this site. The agreement between these data records is excellent for the entire period of measurement. The river stage increased gradually for several hours and then increased abruptly. The rapid rise beginning at 1358 was caused by the arrival of a flow surge initiated by sudden ice motion upstream. The local ice motion began at 1407 and stopped at 1441, just prior to the river stage peak. After the peak, the stage rapidly diminished, reaching a new steady state prior to 1600. The shape of this portion of the stage graph is characteristic of a "drainout," indicating that the source of the surge,

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local channel storage because of the ice, was finite and had been depleted.

CONCLUSIONS

Few river stage measurement methods are available that can be rapidly deployed and are reliable during all conditions, and moving river ice poses a great hazard to those. These experiments over both open water and an ice cover demonstrate that an automatic, stand-alone MMW FM-CW radar system can be rapidly installed to provide continuous, around-the-clock stage data of accuracy comparable to those acquired by a survey team limited to daylight operation. Since the system can be remotely mounted and monitored, personnel are not jeopardized by the hazards involved with direct measurement. Radar stage measurement from above the river eliminates the data reliability problems of systems that require the placement of cables in the river, which are subject to scour. The radar system is also economical because it is identical to that used for ice thickness measurement.

Our initial experiments show promise and have pointed out several modifications for future measurements. A mounting bracket will be installed to eliminate any wind-induced movement of the radar front-end over the river surface. A better maintained nadir look-angle will ensure that the maximum amount of transmitted power will be reflected directly back to the radar, thus improving the signal-to-noise ratio of the system. Additionally, positioning the radar more centrally in the river over free-floating sheet ice rather than closer to the bank avoids shore and grounded ice sheet effects and improves the accuracy of river stage measurements.

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13. ABSTRACT (Maximum 200 words)

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